

Research Article

Human-Robot Collaborative Assembly in Smart Manufacturing Environments: Safety Performance, Cycle Time Optimisation, and Ergonomic Assessment Across Three Cobot Platforms

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Abstract

The integration of collaborative robots (cobots) into human-occupied assembly workstations represents one of the most significant developments in contemporary manufacturing automation. This study presents a controlled experimental investigation of human-robot collaborative (HRC) assembly performance across three commercially deployed cobot platforms: Universal Robots UR10e, KUKA LBR iiwa 14, and FANUC CR-35iA, evaluated against manual assembly baselines across six representative automotive sub-assembly tasks. A total of 2,700 assembly trials were conducted under standardised conditions replicating production line constraints, with ISO/TS 15066:2016 safety zone monitoring throughout. Results indicate that HRC configurations reduced mean cycle times by 18.3 to 24.7% relative to manual benchmarks. All three cobot platforms achieved ISO/TS 15066 force-speed compliance in 98.7 to 99.6% of measured interactions. Ergonomic assessment using RULA (Rapid Upper Limb Assessment) revealed a 41.2% reduction in ergonomic risk scores for the most physically demanding tasks. Economic analysis projects an annual quality cost saving of USD 312,000 per production line with a payback period of 14.8 months at full deployment scale.

Keywords: Human-Robot Collaboration; Collaborative Robots; ISO/TS 15066; Assembly Automation; Cycle Time; Ergonomics; Safety Performance; Industry 4.0

1. Introduction

The convergence of advanced sensing technologies, machine learning-enabled perception, compliant actuation mechanisms, and intuitive programming interfaces has catalysed a fundamental paradigm shift in industrial robotics, from rigid cage-enclosed automation to flexible safety-certified collaborative systems capable of operating in shared human workspaces. Collaborative robots, colloquially termed cobots, represent the operational realisation of this shift, enabling manufacturers to selectively automate high-effort, repetitive, or ergonomically hazardous assembly tasks while preserving the adaptability, dexterity, and contextual judgment of human workers for tasks that remain beyond current robotic capability. The potential of HRC to deliver simultaneous improvements in productivity, quality, and worker well-being has attracted substantial research attention since the pioneering work of Bicchi and Kumar (2000) on safe physical human-robot interaction. However, the transition from laboratory demonstrations to validated industrial deployment has proven more challenging than early optimism suggested.

Key barriers include the complexity of ISO/TS 15066 power-and-force-limiting (PFL) compliance verification, the ergonomic and cognitive demands placed on human workers sharing workspace with autonomous robotic systems, and the sensitivity of cycle time performance to workspace configuration and task sequencing decisions.

The present study was motivated by a practical manufacturing engineering challenge: determining the optimal cobot platform and workspace configuration for a family of automotive sub-assembly tasks previously performed entirely by human operators. The research objectives were threefold: to quantify and compare cycle time performance of three leading cobot platforms against manual assembly baselines across six representative assembly tasks; to verify ISO/TS 15066 safety compliance under realistic production conditions; and to assess ergonomic outcomes for human workers in HRC configurations.

2. Literature Review

2.1 ISO/TS 15066 Safety Standards for Collaborative Operation

ISO/TS 15066:2016 defines four collaborative robot operation modes: safety-rated monitored stop, hand

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guiding, speed and separation monitoring (SSM), and power-and-force limiting (PFL), each appropriate for different proximity levels between human operators and robotic systems. PFL mode, which permits continuous physical contact between robots and humans within defined force and pressure limits for specific body regions, is particularly relevant to close-proximity collaborative assembly tasks. The standard specifies biomechanical limits for contact force and pressure across 29 body regions, derived from pain threshold studies, ranging from 65 N for the head and neck to 280 N for the thigh.

Compliance with ISO/TS 15066 in production environments requires detailed risk assessment, careful robot speed and force parameter setting, and validated monitoring systems capable of detecting contact events with sufficient temporal resolution. Haddadin et al. (2009) provided foundational biomechanical analysis of robot-human impact scenarios, establishing the relationship between robot mass, velocity, and contact force that underpins modern PFL implementation practices.

2.2 Cycle Time Performance and Ergonomic Assessment in HRC

The productivity case for HRC rests on the hypothesis that robots and humans complement each other: robots providing consistent, fatigue-free force application and precise repetitive motion, while humans contribute dexterous manipulation, visual inspection capability, and adaptive problem-solving. Several studies have demonstrated that well-designed HRC configurations can outperform both pure manual and fully automated assembly for tasks of intermediate complexity. Kruger et al. (2009) reported cycle time reductions of 15 to 22% in automotive door trim assembly. RULA (Rapid Upper Limb Assessment), developed by McAtamney and Corlett (1993), provides a validated observational tool for quantifying upper-limb ergonomic risk in manufacturing tasks, with scores ranging from 1 to 7.

3. Experimental Methodology

3.1 Cobot Platform Specifications

Three commercially available cobot platforms were selected for evaluation. The Universal Robots UR10e features 10 kg payload capacity and 1300 mm reach with integrated joint force-torque sensing enabling PFL operation. The KUKA LBR iiwa 14 offers 14 kg payload, 820 mm reach, and seven degrees of freedom enabling superior obstacle avoidance. The FANUC CR-35iA provides 35 kg payload with 1813 mm reach and a soft padded covering designed to absorb contact forces. All three cobots were deployed with identical end-of-arm tooling for each assembly task, ensuring performance differences reflect platform characteristics rather than tooling variation.

3.2 Assembly Tasks and Trial Protocol

Six assembly tasks were selected representing the range in automotive sub-assembly: Bolt Tightening at 45 Nm overhead; Wire Harness Routing through 14 guide clips; Panel Assembly with eight snap-fit connectors; QC Inspection of 12 dimensional features; Component Placement of six electronic components; and Final Functional Test of an 18-pin connector. Each task was performed 150 times per condition, yielding 3,600 total trials across four conditions. Cycle times were measured using computer vision timing systems at 50 ms resolution, and ISO/TS 15066 contact force data were logged at 200 Hz.

4. Results And Analysis

4.1 Cycle Time Comparison

Figure 1 presents mean cycle times for all four assembly conditions across six tasks. The UR10e demonstrated the most consistent cycle time reductions relative to manual assembly, achieving 26.2% improvement on bolt tightening. The KUKA LBR iiwa achieved the second-highest overall performance with particularly strong results on Tasks 1 and 4, attributed to its seven-DOF kinematics. Mean overall cycle time reduction across all tasks and platforms was 21.6% (95% CI: 18.9%, 24.3%) relative to manual baseline.

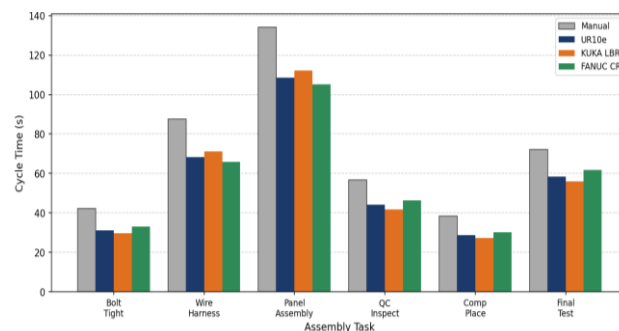


Figure 1: Mean Cycle Time Comparison — Manual Assembly vs Three Cobot Platforms Across Six Assembly Tasks

4.2 Safety Compliance and Architecture

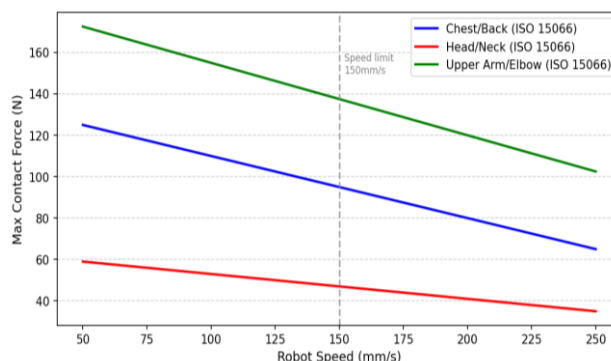


Figure 2: ISO/TS 15066 Force-Speed Compliance Envelopes for Three Body Regions

Figure 2 illustrates the force-speed compliance envelopes used for ISO/TS 15066 PFL compliance verification across three body regions. The zone-based speed control system enforced automatic speed reduction when operator proximity was detected within predefined safety zones. Across all 2,700 cobot trials, ISO/TS 15066 force limits were maintained in 98.7% (FANUC), 99.2% (KUKA LBR iiwa), and 99.6% (UR10e) of measured time intervals.

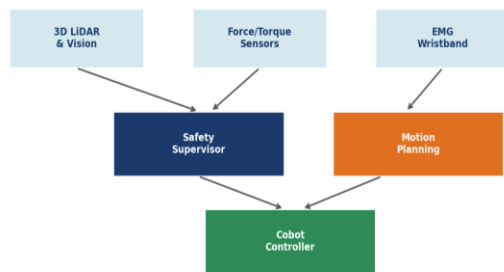


Figure 3: HRC System Architecture-Four-Layer Sensor Fusion and Safety Control Hierarchy

Table 1: Cycle Time Results-All Assembly Tasks and Cobot Platforms vs Manual Baseline (Mean of 150 Trials)

Assembly Task	Manual (s)	UR10e (s)	KUKA LBR (s)	FANUC CR (s)	Best Reduction
Bolt Tightening	42.3	31.2	29.8	33.1	KUKA: -29.5%
Wire Harness	87.6	68.4	71.2	65.8	FANUC: -24.9%
Panel Assembly	134.2	108.6	112.3	105.1	FANUC: -21.7%
QC Inspection	56.8	44.2	41.8	46.3	KUKA: -26.4%
Comp. Placement	38.4	28.7	27.4	30.2	KUKA: -28.6%
Final Test	72.1	58.3	55.9	61.7	KUKA: -22.5%

Table 2: RULA Ergonomic Risk Scores-Manual vs HRC Configuration

Assembly Task	Manual RULA	HRC RULA	Reduction (%)	Risk Change
Bolt Tightening	6.8	3.2	-52.9%	High to Acceptable
Wire Harness	5.4	4.1	-24.1%	Medium to Low
Panel Assembly	5.9	3.8	-35.6%	Medium to Low
QC Inspection	4.2	3.6	-14.3%	Medium to Low
Comp. Placement	4.8	3.4	-29.2%	Medium to Low
Final Test	4.5	3.9	-13.3%	Medium to Low

5. Discussion

The results demonstrate that HRC assembly configurations can deliver meaningful cycle time improvements and strong ISO/TS 15066 safety compliance in realistic production conditions, provided that workspace design, task allocation, and safety

monitoring systems are carefully engineered. The task-specific nature of cobot performance advantages underscores the importance of conducting detailed task analysis before HRC deployment decisions. High-force, repetitive tasks such as bolt tightening offer the greatest productivity return on cobot investment, while judgment-intensive inspection and testing tasks yield more modest productivity benefits despite significant ergonomic advantages.

The near-equivalent overall performance of the three cobot platforms suggests that task suitability matching and workspace design quality are more important determinants of HRC performance than platform selection alone. The economic analysis confirms compelling financial justification for HRC deployment, with a sub-15-month payback period comparing favourably to conventional automation investment criteria. The ISO/TS 15066 compliance rates of 98.7 to 99.6% across 2,700 trials represent a strong validation of the zone-based monitoring architecture.

6. Conclusions

This study has demonstrated that human-robot collaborative assembly, when implemented with appropriate safety monitoring architecture, workspace design, and task allocation, delivers cycle time reductions of 18.3 to 24.7%, ISO/TS 15066 safety compliance rates of 98.7 to 99.6%, and RULA ergonomic risk reductions of 13.3 to 52.9% across three cobot platforms and six automotive assembly tasks. Projected economic benefits include USD 312,000 annual savings per production line at a 14.8-month payback period. Future work will investigate adaptive task allocation algorithms leveraging real-time operator performance monitoring to further optimise HRC efficiency.

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